NUCLEAR MAGICS AT MAGNETOROTATIONAL SUPERNOVA EXPLOSION

V.N.Kondratyev [1,2], Yu.V.Korovina [3], T.V.Mishenina [4]

[1] Physics Department, Taras Shevchenko National University of Kyiv,
03022-UA Kyiv, Ukraine, *vkondrat@univ.kiev.ua*
[2] BLTP, JINR, 141980-RU Dubna, Russia
[3] Moscow Institute of Open Education, 125167-RU Moscow, Russia
[4] Astronomical Observatory, Odessa National University, 65014-UA Odessa,
Ukraine

ABSTRACT. Nucleosynthesis at magnetorotational supernova explosion is considered by employing arguments of nuclear statistical equilibrium. Effects of ultra-strong nuclear magnetization are demonstrated to enhance the portion of titanium product. The relation to an excess of ^{44}Ti revealed from the Integral mission data and galactic chemical evolution is discussed.

Keywords: Stars: supernovae, magnetic field. – Nucleosynthesis: abundances, galactic chemical evolution.

1. Introduction

Supernovae (SNe) represent promising sites for synthesis of heavy atomic nuclei (Woosley, Heger & Weaver, 2002) and give major stellar nucleosynthetic contributions to nuclide inventories during the Galaxy chemical evolution. Magnetization of hot dense plasma due to magnetorotational instability (MRI) is considered as an inherent feature and makes plausible explosion mechanism. In present study we argue that such a feature affects nucleosynthesis (cf., e.g., (Kondratyev, 2004; 2014 and refs. therein) and, in particular, magnetic effects lead to an increase of titanium portion in the synthesis of nuclides close to the iron "peak". Consequently, the characteristic lines of respective nuclei in spectra of astrophysical objects are considerably enhanced and allow for an analysis of synthesized elements. The radioactive decay chain $^{44}\mathrm{Ti} \rightarrow {}^{44}\mathrm{Sc} \rightarrow {}^{44}\mathrm{Ca}$ gives rise to an emission of lines with energies of 67.9 keV and 78.4 keV (from ^{44}Sc *) and 1157 keV (from ^{44}Ca *) of approximately equal intensity. The respective image-mosaics from Integral data (Kondratyev, 2004; 2014) for the Cassiopeia region in various energy ranges of registered photons are presented in Fig. 1. The color (brightness) is proportional to the gamma-quanta flux: as larger the flux as lighter (brighter) the color of a pixel. As is seen the SNR CAS A gives the brightest spot for energies matching ^{44}Sc lines.

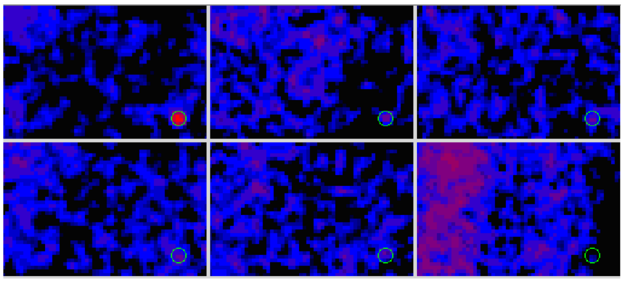

Figure 1: Direction (pixel number) dependence of the registered gamma-ray flux at different energy ranges. top: left – 20–50 keV, middle – 50–67 keV, right – 67–70 keV, bottom: left – 70–77 keV; middle – 77–82 keV, right – 82-100 keV; for the Cassiopeia region. SNR CAS A, (J2000) R.A. 350.86°, decl. 58.81°, indicated by circle.

Table 1: Volume M_{Ti} of nuclides ^{44}Ti (in solar masses M_{Sun}) initially synthesized in young SNe, Tycho, CAS A and SN1987A (see Kondratyev & Korovina, 2015).

SN	$M_{\mathrm{Ti}}[10^{-4}\,M_{\mathrm{Sun}}]$
CAS A	$3.3^{+0.9}_{-0.7}$
SN1987A	3.1 ± 0.8
Tycho	< 0.84

Then ^{44}Ti half-life, about 60 years, allows to determine this isotope initial mass in SN remnants. Table. 1 shows the observational results for the total mass of ^{44}Ti nuclide synthesized in SN explosions from (Kondratyev & Korovina, 2015). These values are significantly larger as compared to model predictions, see. (Woosley, Heger & Weaver, 2002), giving the mass of initially synthesized ^{44}Ti, $M_{\mathrm{Ti}} \sim 10^{-5}\,M_{\mathrm{Sun}}$ (in solar masses M_{Sun}) in an absence of magnetic effects.

2. MRI explosive nucleosynthesis

Abundances of iron group and nearby nuclides are described very successfully within nuclear statistical equilibrium (NSE) approach for over half a century (Woosley, Heger & Weaver, 2002). At such conditions nuclide abundance is determined mainly by the binding energy of corresponding atomic nuclei. The magnetic effects in the NSE were considered by Kondratyev (2014) and refs. therein. Recall that at temperatures ($T \leq 10^{9.5}$ K) and field strengths ($H \geq 0.1$ TT), the magnetic field dependence of relative output value $y = Y(H)/Y(0)$ is determined by a change in the binding energy of nuclei in a field and can be written in the following form

$$y = \exp\{\Delta B / kT\}. \qquad (1)$$

We consider examples of ^{56}Ni and ^{44}Ti. Such a choice of symmetric nuclei, double magic and anti-magic for vanishing magnetization, gives a clear picture of magnetic effects in the formation of chemical elements and fundamental conclusions about transmutation and synthesis of nuclei in ultramagnetized plasma.

The binding energy B can be written as $B = B_{\mathrm{LDM}} + C_{\mathrm{n}} + C_{\mathrm{p}}$, where shell corrections C_{i} for protons and neutrons, and the component B_{LDM} is calculated in semiclassical liquid drop model and varies only slightly in the magnetic field, according to the Bohr-van Leuven theorem, see (Kondratyev, 2014).

Spin magnetization of Pauli type dominates for the neutron magnetic reactivity. Interaction of a field and the spin-magnetic moment corresponding to a spin projection m_{n} on a field vector gives rise to a linear shift of energy levels $\Delta = m_{\mathrm{n}} g_{\mathrm{n}} \omega_{\mathrm{L}}$, where $\omega_{\mathrm{L}} = \mu_{\mathrm{N}} H$ with nucleon magneton μ_{N}, and g_{n} – neutron g–factor. Accordingly, the shell energy in a field H is modified as follows

$$C_{\mathrm{n}}(H) = C_{\mathrm{n}}^{+}(E_{\mathrm{F}} + \Delta) + C_{\mathrm{n}}^{-}(E_{\mathrm{F}} - \Delta), \qquad (2)$$

where the indices + and – indicate a sign of the projection of spin magnetic moment on field direction. The proton magnetic response is represented by a superposition of the field interaction with spin and orbital magnetic moments and exceeds the neutron component for an open shell.

As is demonstrated by Kondratyev & Korovina (2015) at field strengths $H < 10$ TT, the binding energy shows nearly linear H dependence for considered nuclei $B = B_0 + \kappa_i H$ [MeV] with magnetic susceptibility parameters κ_i depending on a nucleus $nucleus = {}^{A}_{N}Z$. For ^{44}Ti the value of this parameter is positive $\kappa_{\mathrm{Ti}} \sim 0.3$ MeV/TT, and in case of ^{56}Ni it becomes negative $\kappa_{\mathrm{Ni}} \sim -0.3$ MeV/TT. Evidently, for anti-magic at zero field strength nuclei the shell energy always increases with field H, and for magic one - decreases, indicating positive and negative values of magnetic susceptibility κ_i, respectively. Then for an average relative yield over MRI region V, see sect. 1, $\langle y \rangle = V^{-1} \int_V d^3 r y(H(\mathbf{r}))$ one gets (Kondratyev & Korovina, 2015)

$$\langle y \rangle = b^{-1}\left(\exp\{a\} + \int_1^b \exp\{a/x\} dx\right)$$

$$= \left(\exp\{a/b\} + \frac{a}{b}\left[\mathrm{Ei}(a) - \mathrm{Ei}(a/b)\right]\right), \qquad (3)$$

where $a = \kappa_i H_0 / kT$, $b = (r_{\mathrm{a}}/r_0)^2$. The radius r_0 relative to the MRI center corresponds to a maximum in field strength H_0, and radius r_{a} is determined from conditions of comparable values for magnetic pressure gradients and gravitational force at R corresponding to material irruption, i.e., $\mathrm{d}H^2(r)/\mathrm{d}r = 4H_0^2/b^2 r_{\mathrm{a}} \sim 8\pi\, \mathrm{GM}\, \mathrm{n}(R)/R^2$. Here the gravitational constant G, and the star mass M inside the bifurcation radius R is related to the matter density $\mathrm{n}(R)$ as $4\pi R^2\, \mathrm{n}(R) = -\mathrm{dM}/\mathrm{d}R$, and the integral exponential function $\mathrm{Ei}(x) = \int_{-\infty}^{x} \frac{\exp\{t\}}{t} \mathrm{d}t$.

In Fig. 2 one sees significant difference for magnetic field dependence of nuclide output, magic and anti-magic at vanishing field. For anti-magic nuclei and, therefore, increasing binding energy with increasing field strength or positive magnetic susceptibility relative volume of nucleosynthesis increases significantly with increasing a. At the same time, the relative production of magic nuclides, i.e., negative value a, is not substantially changed with increasing field. This behavior significantly differs from the case of a spatially uniform magnetization, see Fig. 2, which corresponds to the exponential dependence of $<y>$ or $b = 1$ in Eq. (3). In this case the coefficients of suppression and enhancement are the same with the same absolute value of a. The presence of the diffusion layer, corresponding to a fade-out field strength with increasing r (or $b > 1$) in a real MRI region leads to substantial differences of relevant factors. Significant increase in a synthesis of anti-magic nuclei is accompanied by a slight change in mass volume magic nuclides. Model predictions in the absence of magnetic effects, see. (Woosley, Heger & Weaver, 2002), give the mass of initially synthesized ^{44}Ti, $M_{\mathrm{Ti}} \sim 10^{-5}\, M_{\mathrm{Sun}}$ (in solar masses M_{Sun}). For realistic characteristics of Type II SN explosion (sect. 1) enhancement factor $<y>_{\mathrm{Ti}} \sim 30 - 300$ corresponds to a mass $M_{\mathrm{Ti}} \sim 10^{-3.5} - 10^{-2.5}\, M_{\mathrm{Sun}}$. It is worthy to notice that not all the material ejected from the central part of a star is formed in MRI areas, see (Kondratyev, 2014). Such an enhancement of ^{44}Ti is in an agreement with direct observations in yang SN II remnants, see Table I. At the same time for SN I the ^{44}Ti volume is significantly smaller. One might expect, therefore, noticeable correlations in enrichment of anti-magic nuclides with other metals, e.g., ^{56}Fe, ^{26}Al.

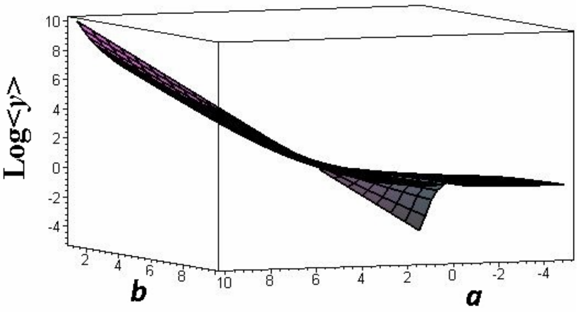

Figure 2: Relative field of nucleosynthesis products depending on parameters a and b.

3. Galactic chemical evolution

An important application of the nucleosynthesis computations is represented by a description of the enrichment of our Galaxy and the Universe as a whole with various chemical elements. Despite considerable progress in the chemical evolution modeling, as well as in the nucleosynthesis computations, a number of issues remain unresolved. In this paper, we dwell on potential sources of calcium and titanium production.

For this purpose we use the abundances of these elements, which we had obtained earlier for the Galactic disc dwarfs (Mishenina et al., 2008), and compared them with the chemical evolution computations (Timmes, Woosley & Weaver, 1995) (Figs. 3, 4). In the recent study (Timmes, Woosley & Weaver, 1995) the yields of isotopes ^{48}Ti and ^{44}Ca, produced by massive supernovae, from Woosley & Weaver (1995) were used to develop a Galactic chemical evolution model. As can be seen from Figs. 3 and 4, the employed data describe the trend of [Ca /Fe] vs. [Fe/H] quite well; however, the adopted yield of isotope ^{48}Ti is insufficient to describe the behavior of [Ti/Fe] vs. [Fe/H]. A similar pattern for calcium and titanium is presented in the study by Timmes, Woosley & Weaver (1995; see their Figs. 25 and 27). It proves that the investigated sources of calcium production, such as massive stars, are dominant suppliers of calcium in the interstellar medium while further improved computations for the titanium sources are required. In respect with titanium the authors point out that "both the ^{48}Ti yield and the ration [Ti/Fe] are sensitive to the parameters of the explosion and the amount of material that falls back onto the neutron star". The nucleosynthesis computations (Woosley & Weaver, 1995) were carried out not accounting for the magnetic field.

We suggest another possible mechanism of additional titanium enrichment when taking into account the increased yield of anti-magic nuclides in ultramagnetized astrophysical plasma. As is seen on an example of the radioactive isotope ^{44}Ti the direct observational data, see sect. 1, confirm such an enrichment which can be understood in terms of magnetic effects. The resulting enrichments of M44 isobars are collaborated with observational data (Kondratyev, 2014; Magkotsios, 2010). The proton magnetic reactivity dominates in a change of binding energy, see Eq. (2). Therefore, one can expect to meet a noticeable increase in production of other titanium isotopes, as well. At the same time a yield calcium isotopes can be expected unchanged because of the proton shell closure, see Eq. (3).

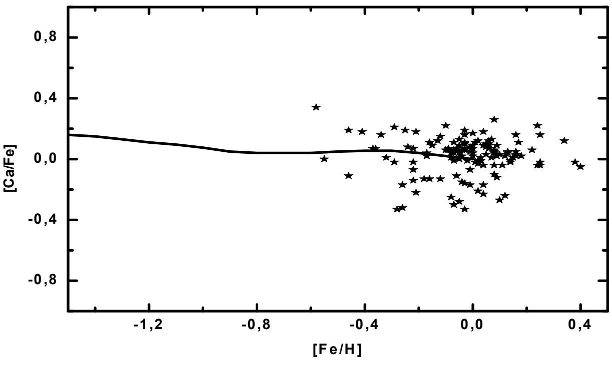

Figure 3: Comparison of observed abundance of Ca (Mishenina et al., 2008, marked as asterisks) with the trend of galactic chemical evolution (Timmes, Woosley & Weaver, 1995, marked as solid line).

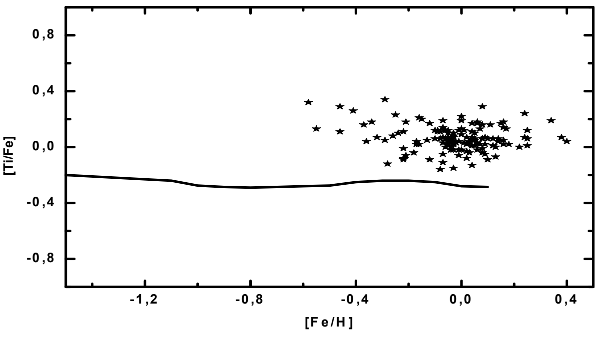

Figure 4: The same as Figure 3, but for Ti abundance.

4. Conclusion

Effects of ultra-magnetized astrophysical plasma in supernovae on synthesis of chemical elements were investigated at conditions of nuclear statistical equilibrium. Magic-antimagic switches in the nuclear shell structure in varying magnetic field lead to an increase of titanium binding energy and, consequently, to a noticeable increase of the portion of ^{44}Ti in explosive nucleosynthesis products. Magnetic effects in nuclide creation are favorably compared to observational Integral data and galactic chemical composition.

Acknowledgements. This work is supported in part by Integral scientific data center and by the Swiss National Science Foundation (SCOPES project No.~ IZ73Z0152485).

References

Kondratyev V.N. et al.: 2004, *Proc. 54th Intern.Symp. on Nuclear Spectroscopy and Structure of Atomic Nuclei* (Belgorod, Russia), p. 83.

Kondratyev V.N.:2014, *EPJ A*, **50**, 7.

Kondratyev V.N., Korovina Yu.V.: 2015, *JETP L*, **102**, 131.

Mishenina T.V., Soubiran C., Bienayme O. et al.: 2008, *Astron. Astrophys.*, **489**, 923.

Magkotsios G. et al.: 2010, *ApJS*, **191**, 66.

Woosley S.E., Weaver T.A.: 1995, *Astrophys. J. Suppl. Ser.*, **101**, 181.

Woosley S.E., Heger A., Weaver T.A.: 2002, *Rev. Mod. Phys.*, **74**, 1015.

Timmes F.X., Woosley S.E., Weaver T.A.: 1995, *Astrophys. J. Suppl. Ser.*, **98**, 617.